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MONITORING THE SETTING OF BONE CEMENTS USING ULTRASONIC BACKSCATTERING.

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ABSTRACT

We report a method to monitor the setting of bone cement using ultrasonic signals. By analysing the backscattered fields using pulse-echo-technique and a single transducer, we show that it is possible to describe the acoustic properties of the material. The apparent backscattering transfer function has been measured in 4 experiments. It consists in comparing the backscattered energy corresponding to a nearby volume of the material with a signal reference in a frequency average of the backscattered power-spectrum. This ultrasonic technique opens new doors to develop real-time monitoring systems for bone regeneration in dental implantology applications.

RESUMEN

Se ha desarrollado un método para controlar el proceso de fraguado de cemento óseo mediante la monitorización ultrasónica.
La señal de retrodispersión ultrasónica se ha generado y detectado mediante una técnica eco-impulso en modo A scan. Utilizando la técnica de eco-impulso es posible describir propiedades acústicas del material que están relacionadas con su estado físico durante el proceso de fraguado. Se ha calculado en diferentes 4 experimentos la función de transferencia de backscattering aparente (ABTF), consiste en comparar la energía correspondiente a un volumen cercano del material con una señal de referencia, analizando un promedio del espectro de potencia determinado. La monitorización del fraguado del cemento óseo mediante el analisis de la retrodifusión, permite identificar la fase (liquida/solida) en qué se encuentra el material en cada instante. Esta técnica ultrasónica abre nuevas puertas para desarrollar sistemas de monitoreo en tiempo real para la regeneración ósea en aplicaciones de implantología dental.

INTRODUCTION

In the context of dental implantology the loss of tooth affects the quality and thickness of the bone [1]. To get stability and durability of dental implants, it is necessary to have sufficient bone volume. In cases that the bone volume is insufficient, the dentists perform Guided Bone Regeneration (GBR) by sinus augmentation [2]. In this operation, a window in the lateral area is performed, the Schneider membrane is lifted, and a bone graft inserted. The window is coated with a pericardium membrane, and then the regeneration process has a healing phase of 6 months. The maxillary sinus floor augmentation procedure was first proposed by Tatum 1974 [2]. Sometimes, this process fails: S.Annibali in 2008 [3] and J.Acero 2011 [4] explain how different complications may appear postoperatively, i. e. the soft tissue growth or failed osseointegration.

Dentists use radiological techniques for diagnosis in odontology. There are several types of dental radiographs as for example, the panoramic and lateral radiography, the computerized tomography (dental scanner), the orthopantomography and the teleradiography or Cone Beam Computerized Tomography (CBCT), all these based on x-rays. An important drawback of these techniques is that they have risks, such as excessive exposure to ionizing radiation [5-6]. For this reason, ultrasound techniques are proposed to monitor the process of bone regeneration since they are non-invasive and non-ionizing.

Ultrasounds have been used to measure bone density [7-8]. Different devices exist in the market for the diagnosis of osteoporosis with ultrasounds, for calcaneus or phalanx [9-10]. For doing so, different parameters are considered and calculated. The Speed Of Sound (SOS), in the material is related to its physical magnitudes, this parameter is an intrinsic quantity of the material. To measure it, the difference in time between two received echoes and the thickness of the sample is analyzed. Broadband Ultrasound Attenuation (BUA) is a parameter that indicates the apparent attenuation in a given bandwidth and is related to the attenuation of sound propagation in the material analyzed. This parameter is used in many works [9-13] to estimate the density of the bone. It is proposed here to use the ultrasonic impulse-echo-technique to perform the experiments. The impulse-echo-technique is useful to perform backscatter analysis, the reflected signal can be captured.

Backscattering is a type of diffuse reflection that corresponds to the interference of multiple reflected waves from the scatterers or the internal microstructures. The last ten years, different parameters based on the backscattering energy have been used and defined. The Apparent Integrated Backscatter (AIB) is a measure of the frequency-averaged (integrated) backscattered power contained in some portion of a backscattered ultrasonic signal. [14]. In the present work, setting process of calcium sulphate has been monitored. The parameters of AIB and Speed of sound has been analysed.

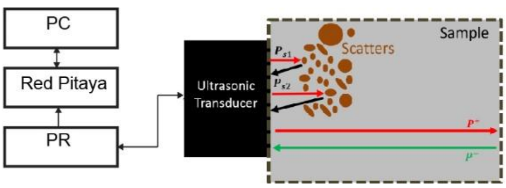

Figure 1. Experimental setup. The signal has been transmitted with the pulser-receiver, the received signals has been recorded with the red pitaya, and has been analyzed with MATLAB.

METHODS

Phantom preparation

Calcium sulphate type IV $CaSO_4$ (Ventura Pinkmod) was used as a bone cement. This material was used in the past for guided bone regeneration [15-19]. Its acoustic and mechanic characteristics are similar to the bone regeneration as in the setting process a change of state is produced from liquid to solid. This process has a setting time of around 20 minutes. Four experiments were carried out with the following mixing ratio: 23 ml of water and 50 g of powder. The material has been deposited in a cylindrical container with a diameter of 3.6 mm, obtaining pieces with 18 mm of thickness. The setting process of the bone cement has been monitored by an ultrasonic system every two seconds.

Ultrasonic measurement

An Olympus V382 transducer with a central frequency f 3.5 MHz and a bandwidth of 2.34 MHz to -6 dB has been used. The transducer has been placed directly on the recipient with the sample. The impedance has been adapted with a layer of Vaseline. Measurements have been made for 50 minutes every 2 seconds. The temperature has been measured using a data loggers with a temperature sensor. An ultrasonic Pulser-receiver (Panametrics Model 5072) has been used as a reception emission system. The received signal has been digitized with a Red Pitaya, at a sampling frequency of 125 MHz. Finally, MATLAB has been used to develop an analysis software. The acoustic properties monitored in acoustic cement have been the propagation speed and backscatter parameters. With this analisis we evaluate three parameters during the setting process:
1.- the speed of sound propagating in the medium. It has been fitted with respect to time to an arctangent function:

$$y(t) = c_1 + (c_2 - c_1)\tan^{-1}\left(\gamma\frac{t - t_m}{\pi} + \frac{1}{2}\right)^{\beta} \quad (1)$$

where c_1 is the speed of sound in liquid state (in m/s), c_2 is the speed of sound in solid state (in m/s), γ is related to the duration of the transition from liquid to solid state (in s^{-1}), t is the time of the experiment (in s), t_m is the time in the middle of the process (in s) and β is an adimmensional parameter related to the symmetry of the function.
2.- The apparent backscatter transfer function (ABTF), which represents the backscattered power from the specimen [14]:

$$ABTF = 10\log_{10}\left(\frac{P_{specimen}(f)}{P_{reference}(f)}\right) \quad (2)$$

where $P_{specimen(f)}$ is the frequency-dependent power in a selected portion of the backscatter signal and $P_{reference(f)}$ is the frequency-dependent power of a first echo from a steel plate reflector and

3.- The apparent integrated backscatter coefficient (AIB) is a measure of the frequency-averaged backscattered power for the frequency response of the measurement system. [14]:

$$AIB = \frac{1}{f_{max} - f_{min}}\int_{f_{min}}^{f_{max}} ABTF(f)df \quad (3)$$

where f_{min} and f_{max} is the range -6dB.

RESULTS

Fig. 3a shows the evolution of the temperature against time during the setting process. It is approximately stable the first 19 minutes. After this time it increases because the powder liquid reaction starts and the transition to the change of state is produced. The temperature continues to rise as the reaction in the material is produced, until it collapses at minute 25' and starts to cool smoothly. While the material is cooling, the change of state ends, and the material is transformed from liquid to solid state. In Fig.3b, the speed of sound is represented for the same time as the temperature. The initial speed of sound of the cement is 1477.2m/s, close to value of liquid water. It can be observed that the change of the state and initial heating of the material corresponds to an abrupt increase of the speed of sound. Once the material is solidified the speed of sound reaches a stable value close to 2700m/s. The temporal dependency of the speed of sound during the setting process of bone cement presents a symmetric function against time and it has modeled with an arctangent fit in order to describing it quantitavely (it is represented in dashed line in Fig. 3b). In table 1, different parameters of the fit for the four different experiments corresponding to the setting process of the same material.

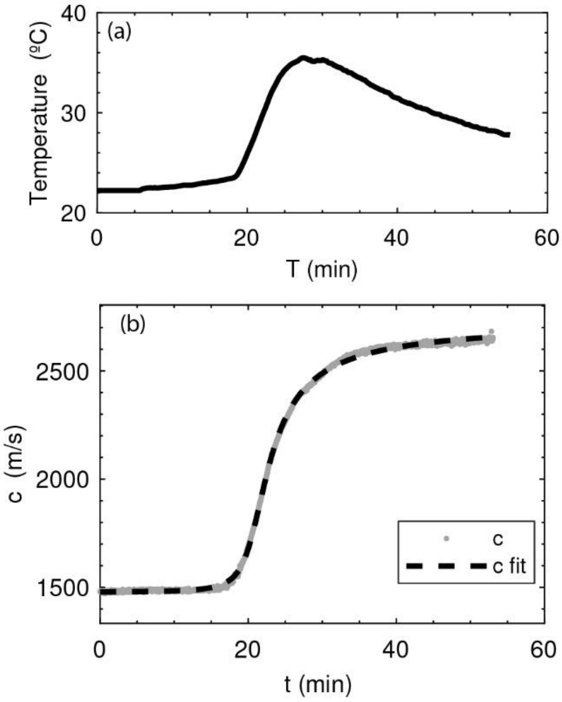

Figure 2. The temperature measured in the experiment in ºC (a) and the speed of sound measured and close-fitting. (b)

	β	γ	t_m (min)	c_1 (m/s)	c_2 (m/s)
E1	2,1326	0,3464	20,7117	1477,2	2731,5
E2	1,9631	0,3413	20,8448	1553,9	2919,5
E3	1,3641	0,327	19,9499	1553,9	2919,5
E4	1,7521	0,3671	20,1358	1627,2	3049,8
Mean	1,8030	0,3454	20,4106	1514,5	2797,9
Std	0,3314	0,0166	0,4347	98,0	242,8

Table 1: Values of the arctangent function fitted for the four experiments, and the mean and the standard desviation.

The parameter c_1 accounts for the speed of sound at the initial liquid state of the sample. The mean value for c_1 is 1500 $\pm$ 100 m/s. This speed is similar to the speed of sound of the water, as the material in the initial process is mainly water with undissolved powder. The information from the c2 concerns the speed of sound sample in solid state at the end of the setting process. The mean value for the four experiments of the solid state speed is 2800 $\pm$ 200 m/s. The parameter t_m is fitted in order to establish the middle time for the setting process. It is around 20 min and 24 sec $\pm$ 0,24 seconds. Analysing the results of γ, the factor that control the duration of the transition from liquid to solid is 1.8 $\pm$ 0.3. The factor β is 0.345 $\pm$ 0.016. The relative dispersion is very low wich means that for the four experiments the SOS has the same symmetry.

The AIB is represented in Fig.4 along the setting process of the bone cement, obtained from the amplitude of the ultrasound 1st echo. Before minute 10' the sample is in liquid state and the AIB has a mostly constant value with a hifh dispersion as the amplitude of the backscattering signal is very low. After minute 20' the value of AIB is suddenly increased as the setting process is started and the amplitude increases. After some oscillations the value of AIB reaches the maximum of -2dB. From minute 30' the sample is in solid state and the integrated bacscattering is smoothly increasing from -5dB to 0dB at the end of process. The amplitude of the backscattered signal (represented in dahsed red) accounts of the dispersion of the AIB results: small amplitude values provides high dispersion of the AIB. Fig. 4 represents the correlation of AIB with SOS. In the figure, two agglomerations of experimental points can be highlighted (around 1500m/s and 2500m/s). The major part of the experimental measurements of the 4 experiments (E1, E2, E3 and E4) during the setting process are in these two groups, that correspond to the liquid and solid states. The rest of experimental points correspond to the transition of state.

There is a positive correlation between the AIB and the speed, with a concentration of results in two zones, an initial one, where the material is in a liquid state and the speed and the AIB have minimum values, and another area where the material is solid and the speed and the AIB have maximum values

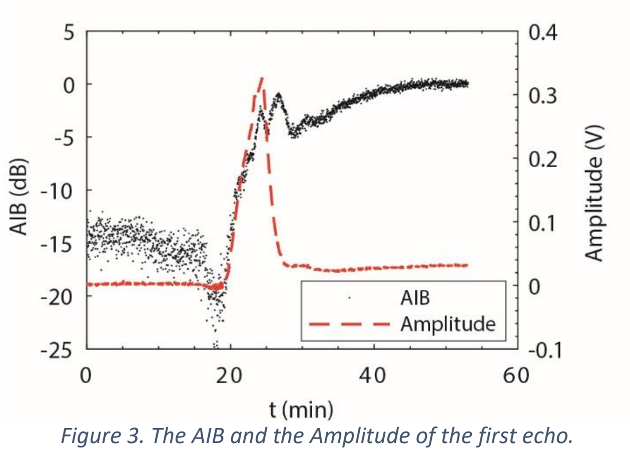

Figure 3. The AIB and the Amplitude of the first echo.

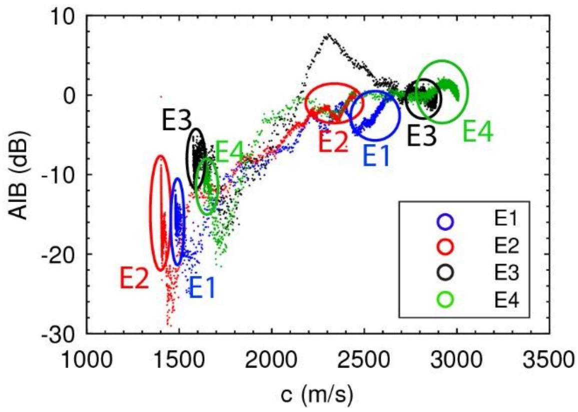

Figure 4. The correlation of AIB and SOS for the four experiments.

CONCLUSION

The speed of sound and AIB has been calculated from backscattering ultrasonic signals in 4 experiments and represented against time during the setting process bone cement. Results show that both parameters are related to the physic state of the bone cement account for the whole process; from the liquid state to the solid state, as well as the transition phase in between. The speed of sound has been fitted to a A positive correlation between the speed of sound and AIB is observed, which indicates that the AIB is a consistent parameter to determine the temporal features of the change of state change in the sample.

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